

# Applications of Adjoint Methods for Aerodynamic Shape Optimization

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**FAA/NASA Joint University Program for Air Transportation**

**Quarterly Review**

**MIT**

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**Princeton University**



# Outline

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- **Progress Report / Review**
  - **3D Design Code for Unstructured Grids**
- **Application of Adjoint Method to Rotating Geometry**
  - **Penn State ARL (James Dreyer) - Princeton University collaboration**
  - **Hydrodynamic Propulsors**
- **Summary**



# Adjoint Based Shape Optimization for Unstructured Grids

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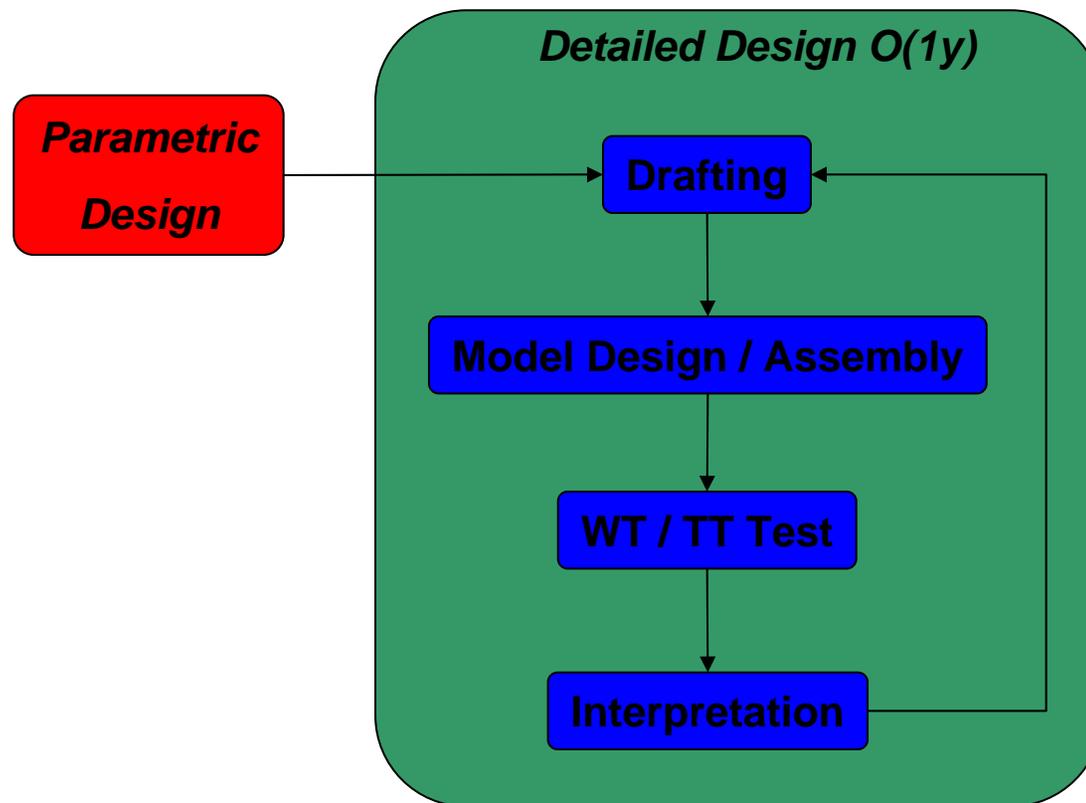
- **Control Theory Approach as used on structured grids**
- **Challenge in computation of the gradient for unstructured grids**
  - **Reduced gradient formulation**
  - **Gradient is derived solely from the adjoint solution and the surface displacement, independent of the mesh modification**
- **Methods to impose thickness constraints**
  - **Cutting planes at span-wise locations & transformations**



# Motivation

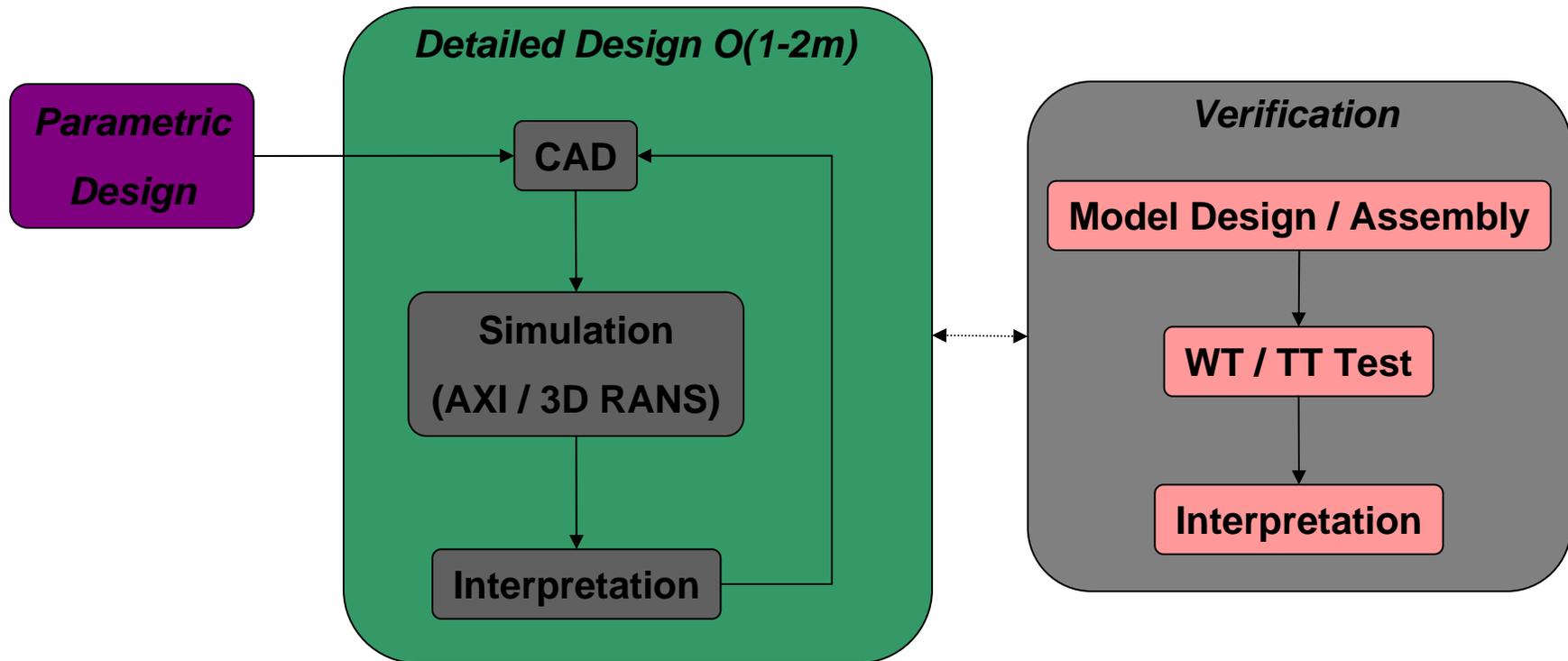
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## Historical Propulsor Design Methodology – “cut & try”



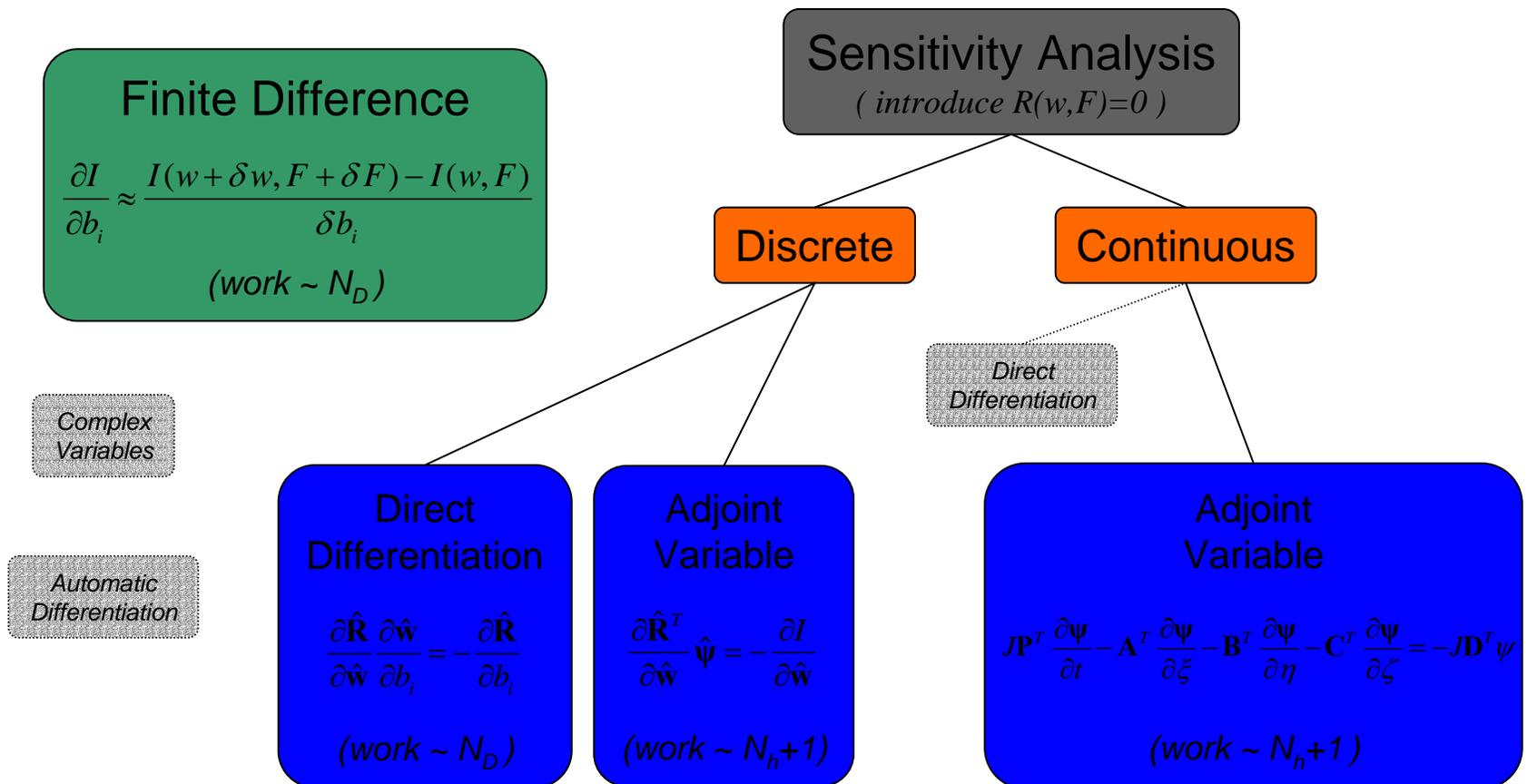
# Motivation

Current Propulsor Design Methodology – “virtual cut & try”



# Background

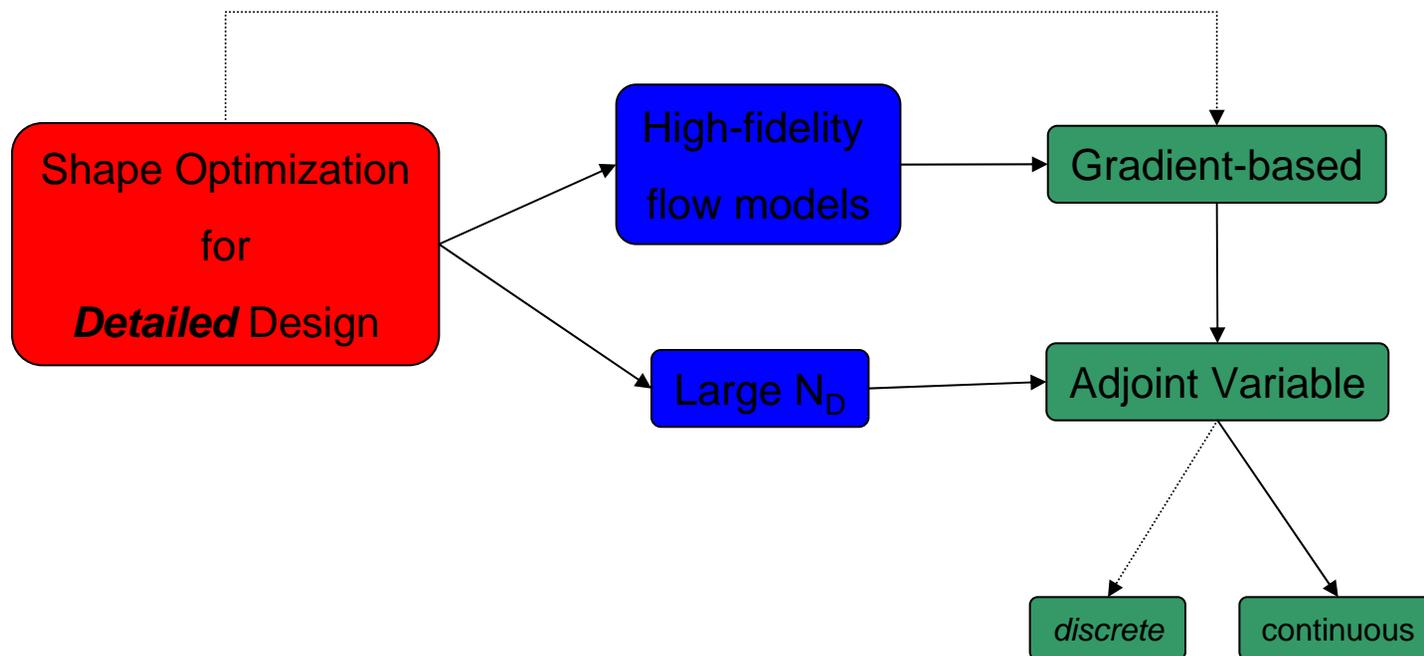
- Focus of gradient-based approaches has been on the *efficient* determination of the cost function gradient  $\partial I^T / \partial \mathbf{b}$



# Approach

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- Shape Optimization of Propulsors



# Flow & Adjoint Solvers

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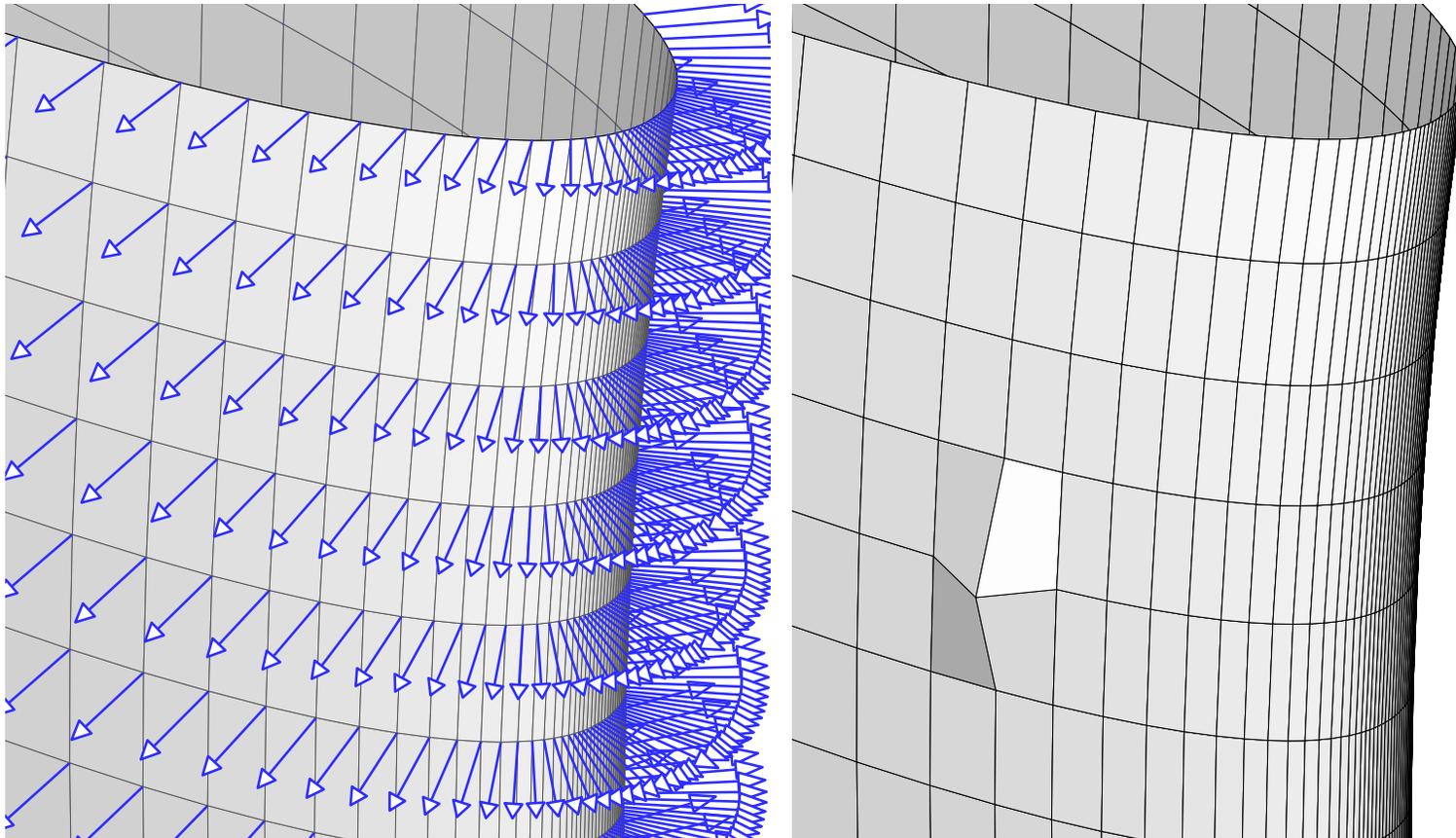
- Cell-centered finite volume on hexahedra
- Central difference + scalar,  $O(3)$  artificial dissipation
- Jameson-type Hybrid Multistage Scheme (5-3)
- Local time-stepping, multigrid (W)
- Domain decomposition / MPI
- Baldwin-Lomax algebraic eddy viscosity

***SAME algorithm applied to Adjoint equations***



# Design Variables

- Surface mesh point movement in the direction of the local quasi-normal vector,  $\mathbf{e}_s = \delta b \vec{t}$



# Shape Optimization

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Gradient-based approaches:  $\delta \mathbf{b}_k = \alpha_k \mathbf{d}_k$

$$\mathbf{d}_k = -\mathbf{G}_k$$

- **Steepest Descent:**
  - Relatively tolerant of errors in the gradient
    - ⇒ Partially-converged flow & adjoint solutions
  - NO univariate searches
- **Conjugate Gradient & Quasi-Newton**
  - Very accurate gradient
    - ⇒ Fully-converged flow & adjoint solutions
  - One-dimensional minimization
    - ⇒ O(4) fully-converged flow solutions





# Application

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- Marine propulsor / pump blade shape optimization
- Cost Function: *Inverse Design*

$$I = \frac{1}{2} \int_{B_b} (p - p_d)^2 dS ,$$

$p_d = \text{target pressure}$



# Inviscid Inverse Design

- **Flow Field Boundary Conditions:**

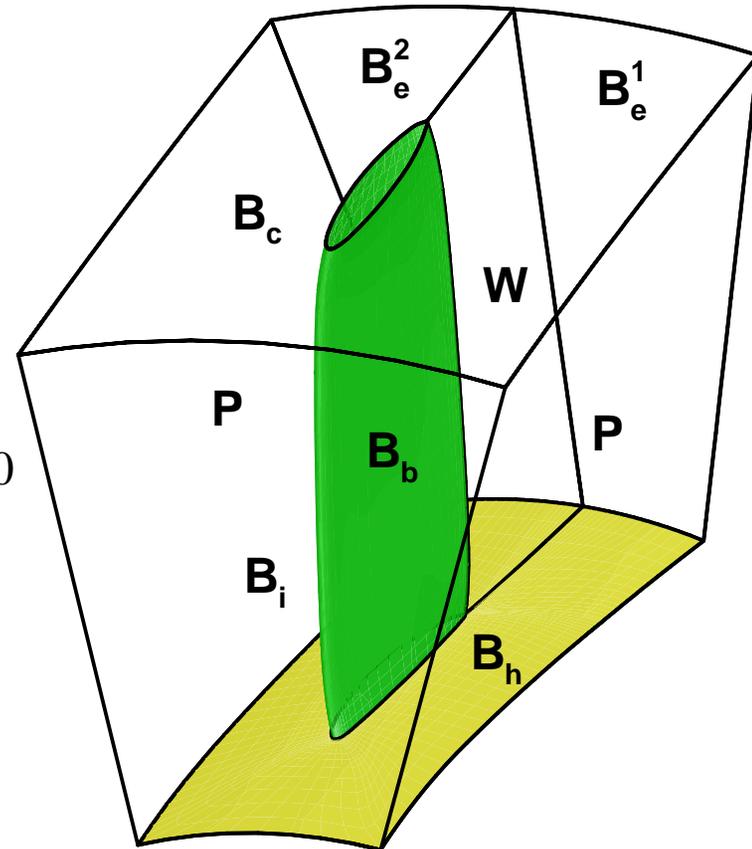
$B_b, B_h, B_c$ :  $\vec{V}_w \cdot \vec{n} = 0$ ,  $\partial p / \partial n = \text{normal momentum}$

$B_i$ :  $v_x(r), v_r(r), v_\theta(r)$  specified,  $\partial p / \partial n = 0$

$B_e^1, B_e^2$ :  $\mathbf{w} = \mathbf{M}_\xi (\mathbf{L} \mathbf{M}_\xi^{-1} \mathbf{w}^\infty + (\mathbf{I} - \mathbf{L}) \mathbf{M}_\xi^{-1} \mathbf{w}^i)$

P: *periodic*

W: *overlap*



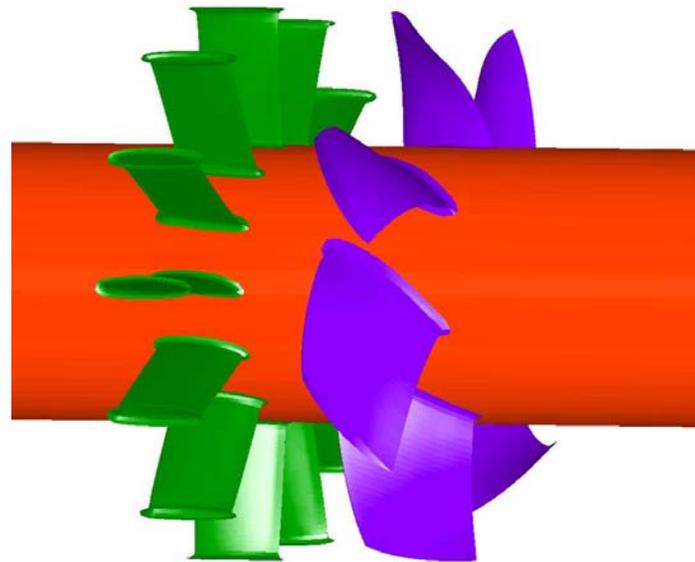
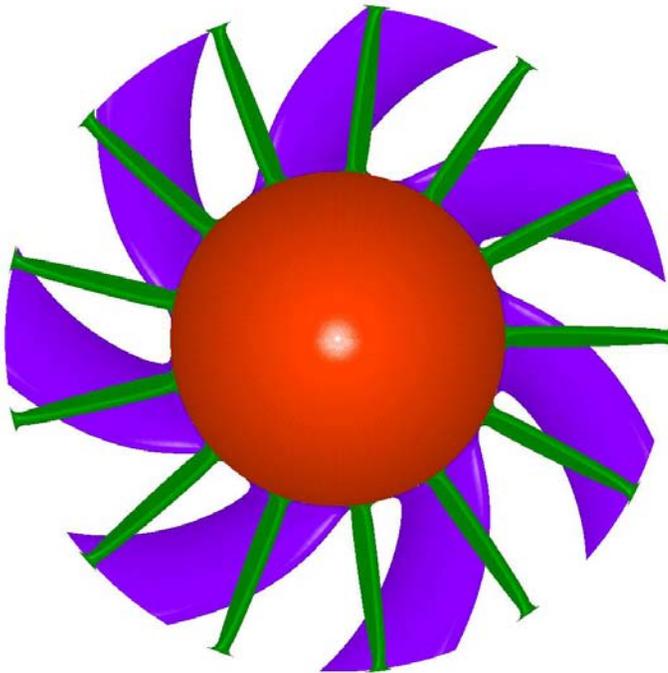
# Inverse Design Cost Function Results

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HIREP

High REynolds number axial flow Pump test facility at ARL Penn State

2 blade rows: IGV (13), Rotor (7)



*D = 42 in.*  
*V = 35 ft/sec*  
*RPM = 260*

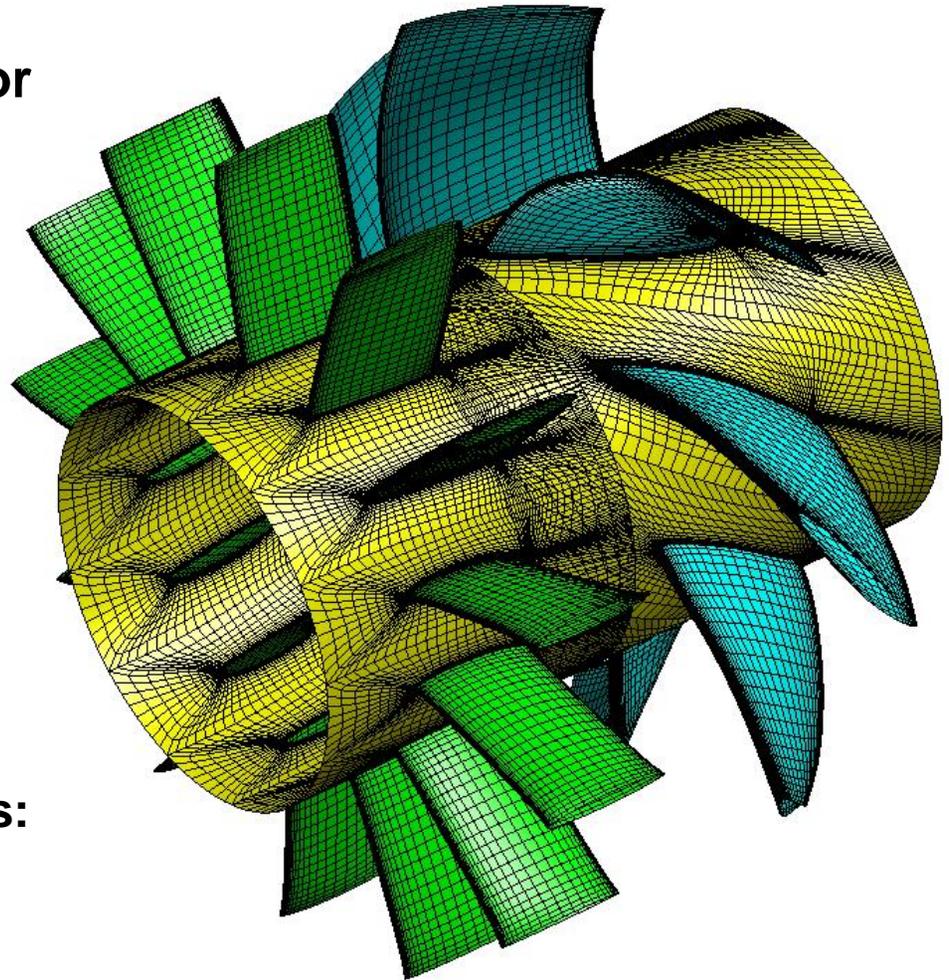


# Inviscid Results

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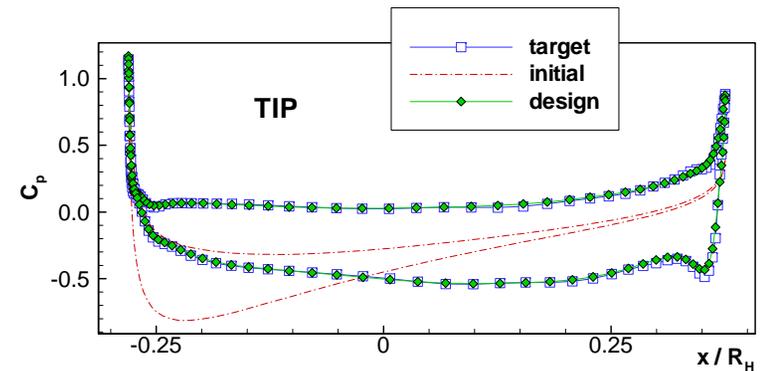
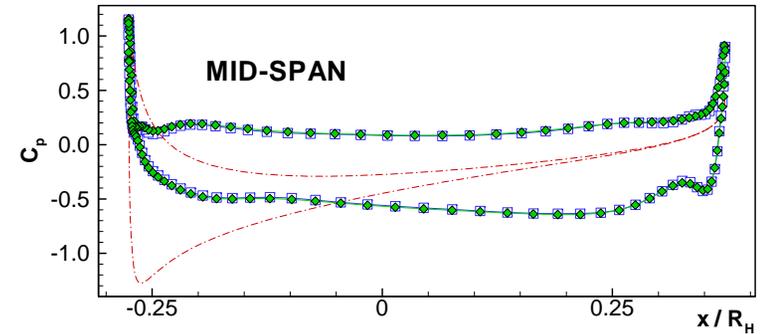
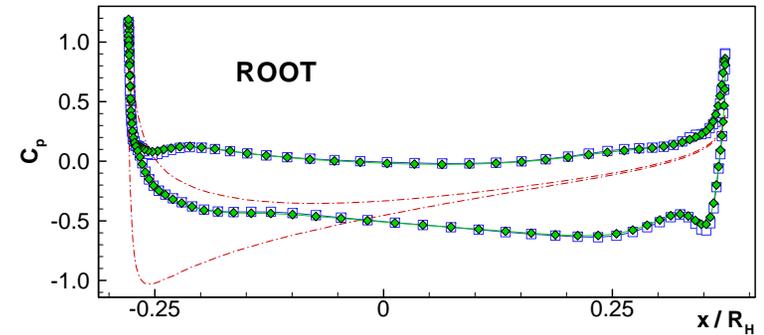
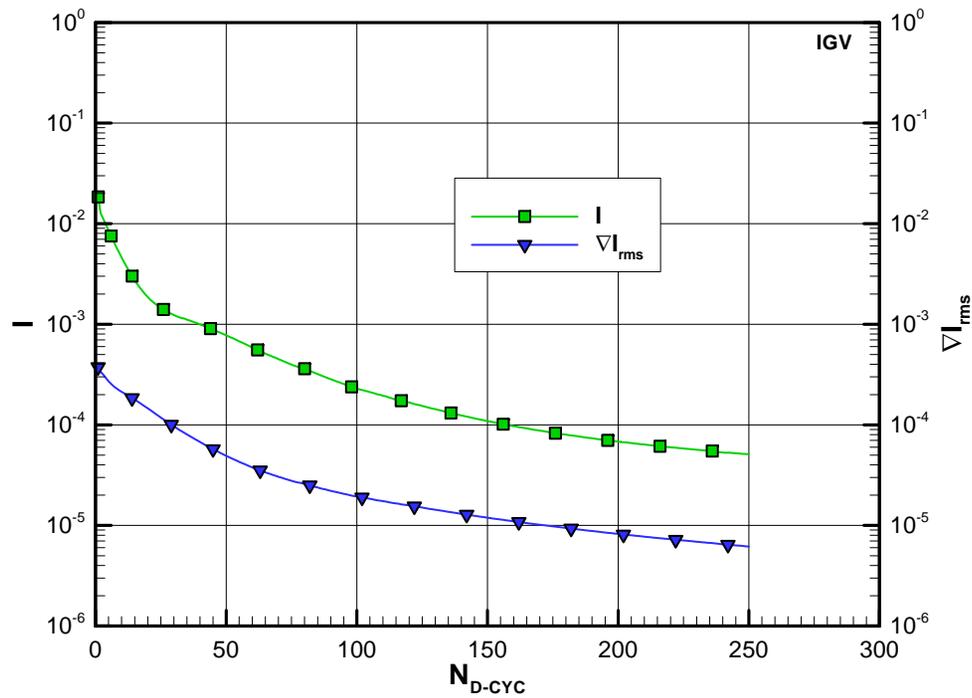
- **Inlet Guide Vane (IGV) & Rotor**

- **Governing equations:**  
*3D incompressible Euler*
- **Initial blade:**  
NACA 0012 sections
- **Geometric constraint:**  
Fixed chord line
- **Target pressure distributions:**  
Separate simulations of  
HIREP IGV & rotor

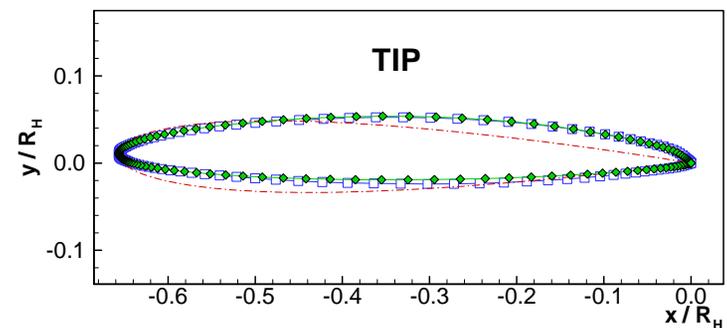
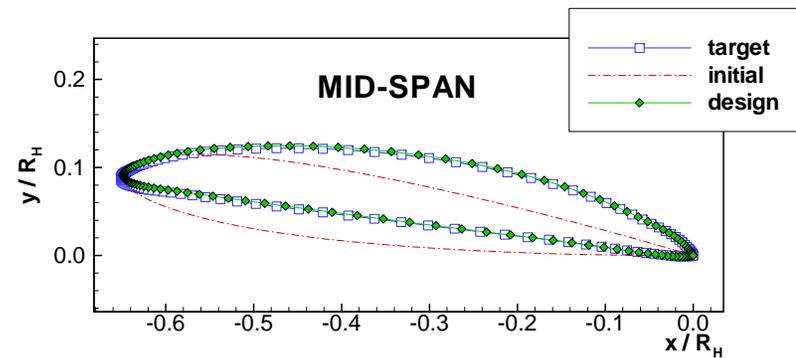
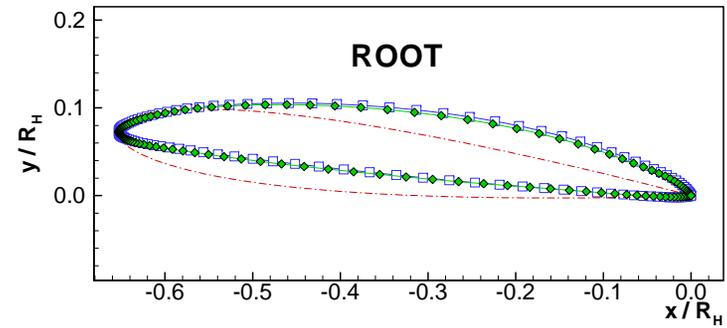
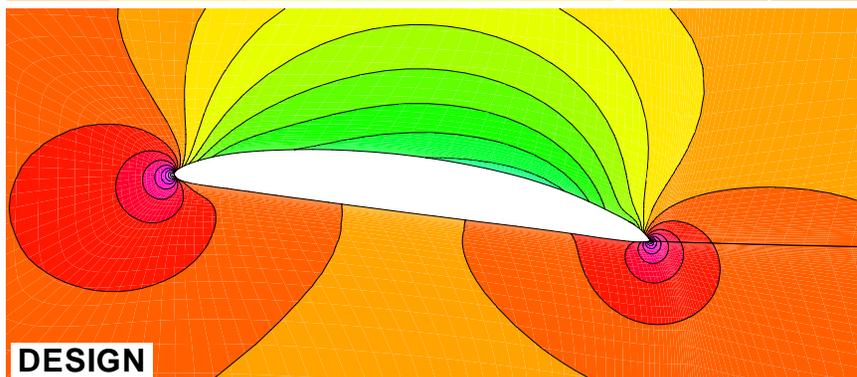
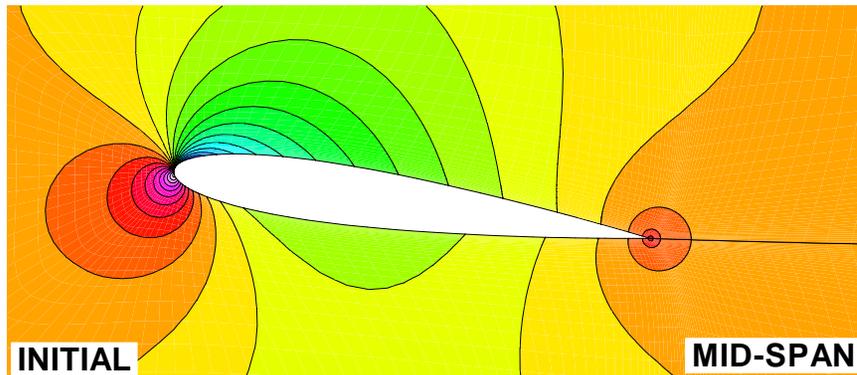
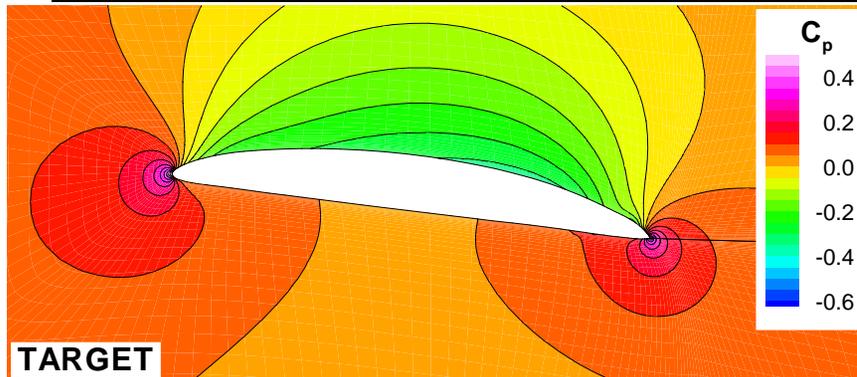


# Inviscid Results - IGV

- IGV Inverse Design  
(no rotation)  
 $N_D = 6321$

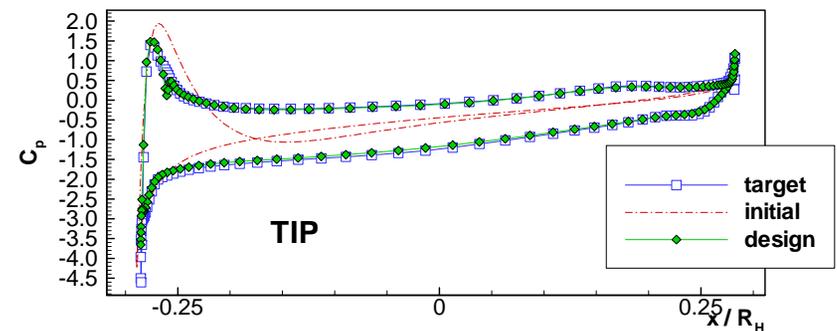
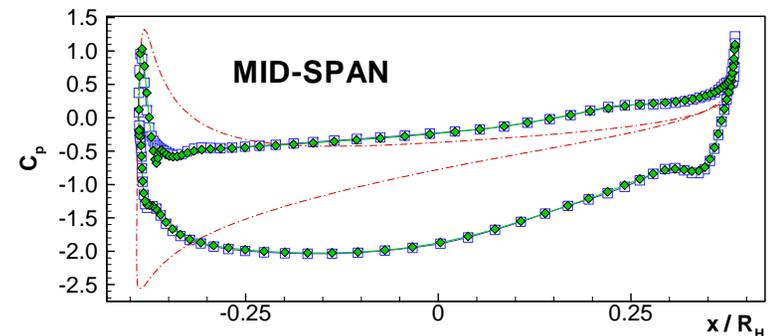
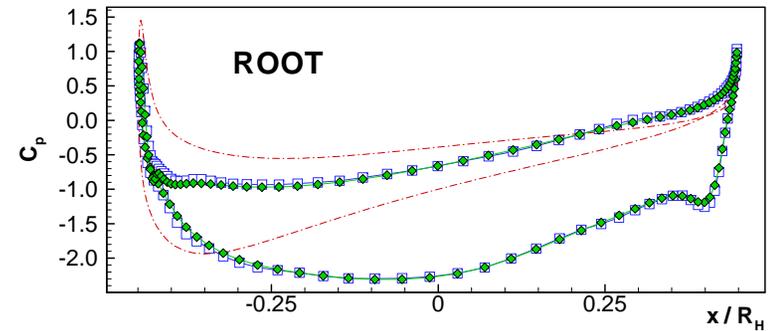
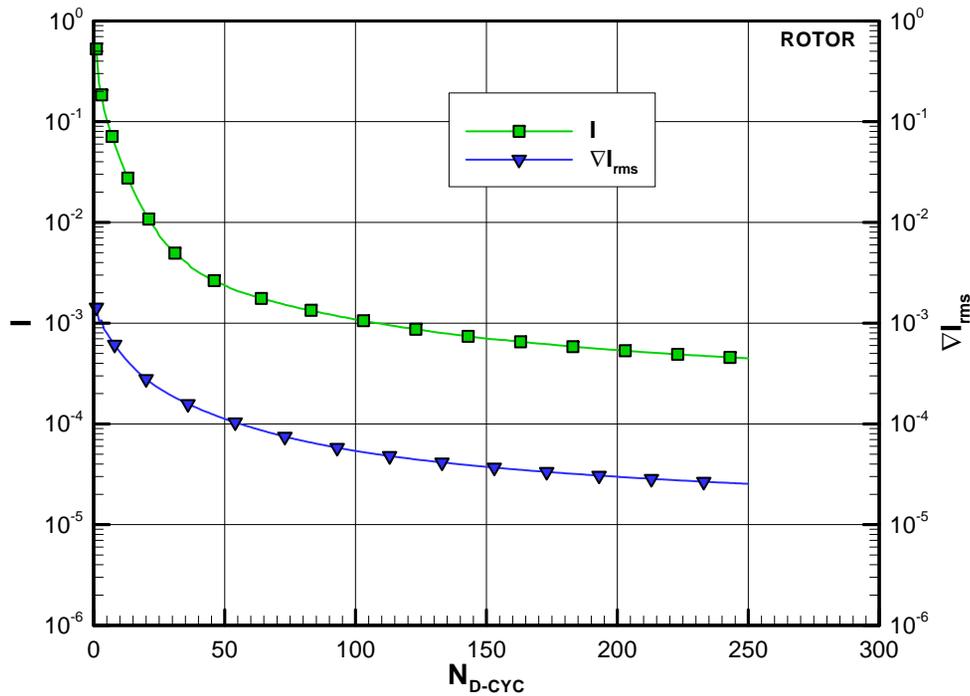


# Inviscid Results - IGV

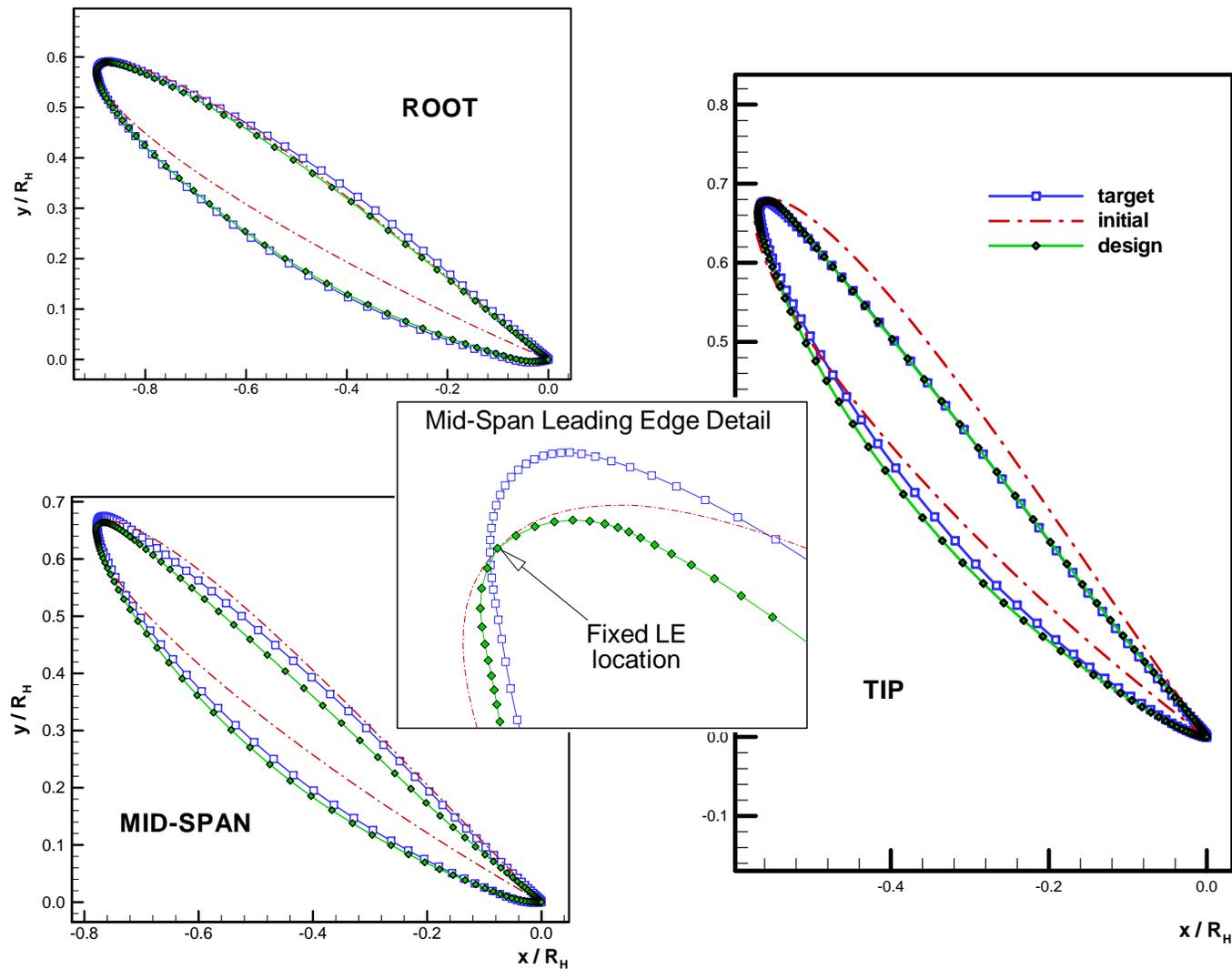


# Inviscid Results - Rotor

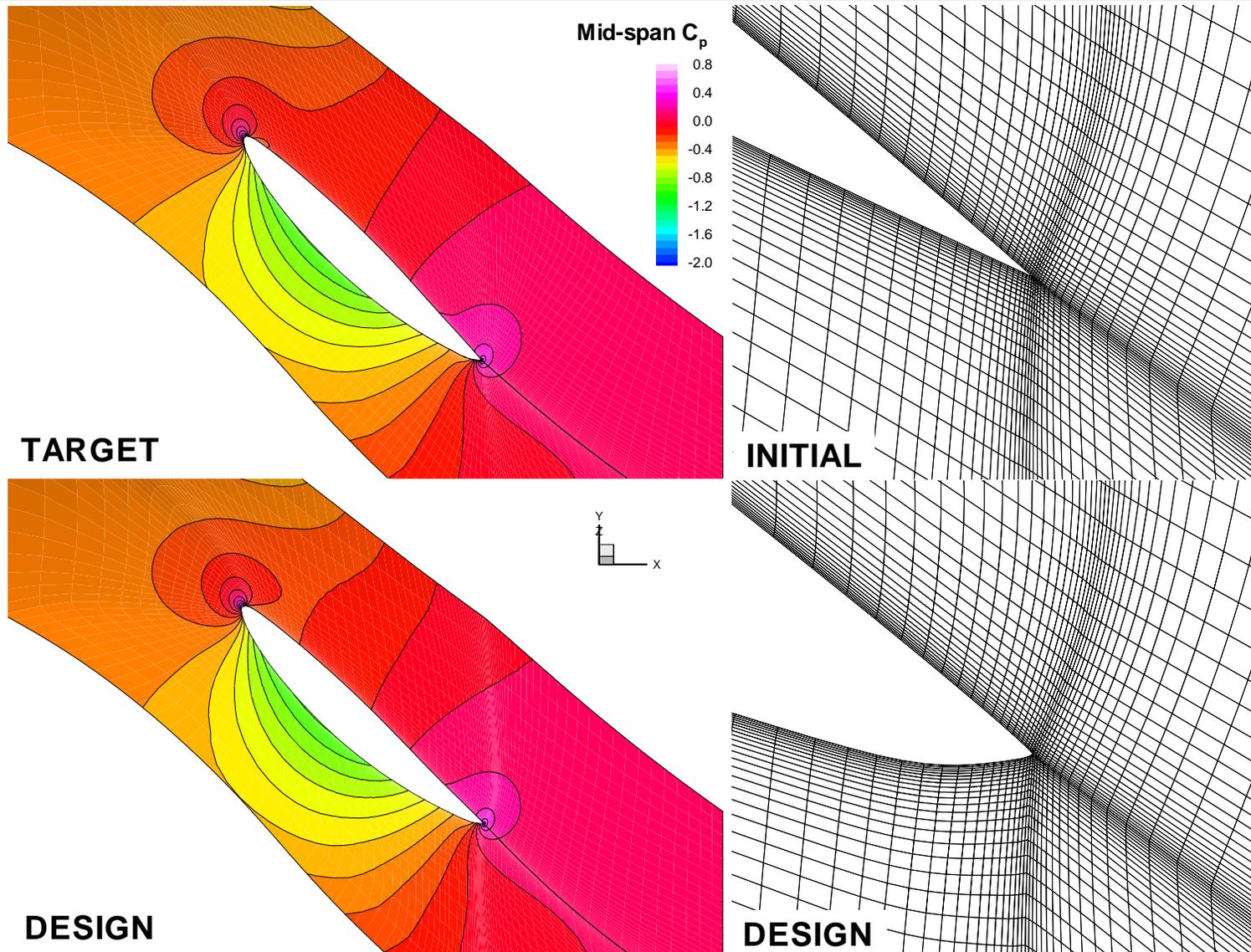
- Rotor Inverse Design  
(260 RPM)  
 $N_D = 6321$



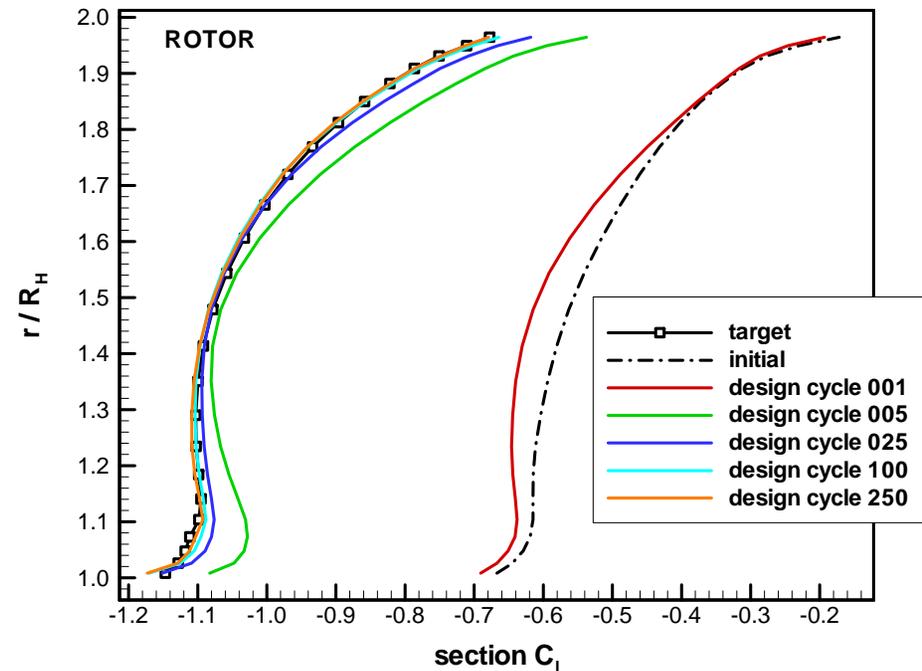
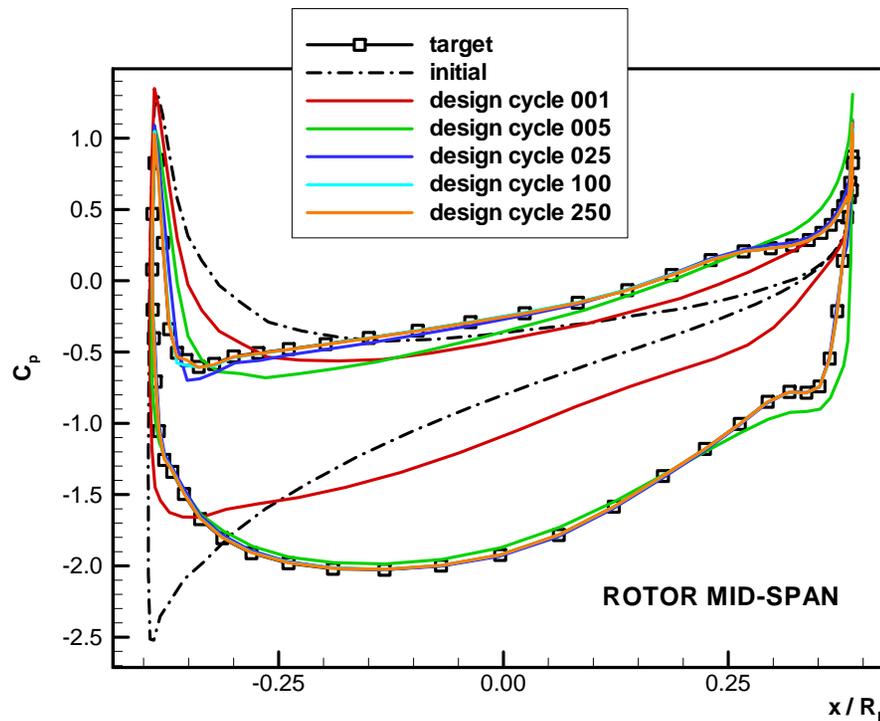
# Inviscid Results – Rotor Detail



# Inviscid Results – Rotor Trailing Edge Detail



# Inviscid Results – Rotor Inverse Design Convergence



# Inviscid Results - Summary

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- Design Cycle Timings

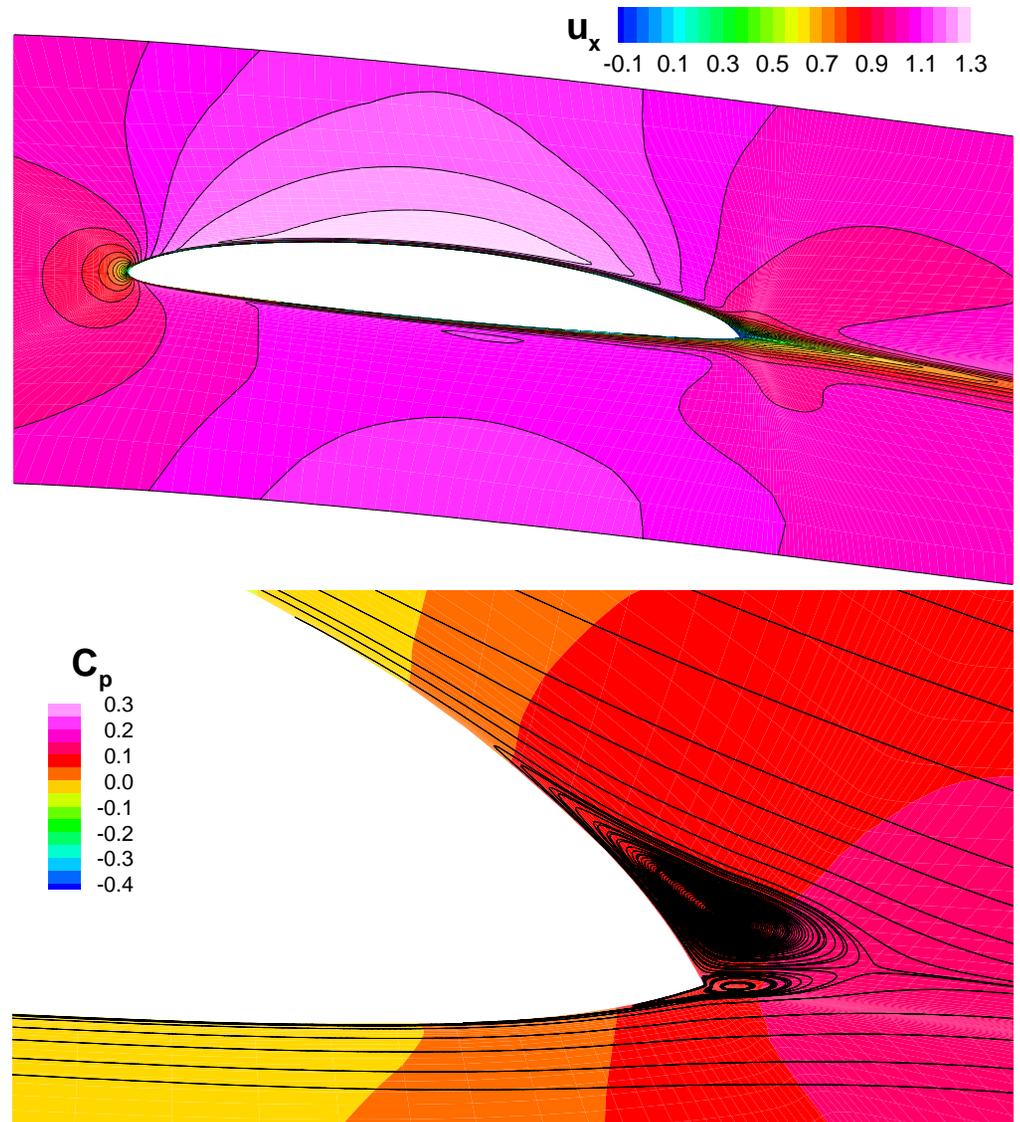
<i>COARSE MESH</i> <i>41,225 mesh points</i> <i>1,625 design variables</i>	<i>Wall Clock</i> <i>8 CPUs (PIII)</i> <i>seconds</i>	<i>% of Total</i>	<i>FINE MESH</i> <i>312,081 mesh points</i> <i>6,321 design variables</i>	<i>Wall Clock</i> <i>16 CPUs (PIII)</i> <i>seconds</i>	<i>% of Total</i>
<i>Flow Solution</i>	<i>5.39</i>	<i>48</i>	<i>Flow Solution</i>	<i>22.21</i>	<i>46</i>
<i>Adjoint Solution</i>	<i>5.21</i>	<i>46</i>	<i>Adjoint Solution</i>	<i>21.20</i>	<i>44</i>
<i>Gradient / Re-meshing</i>	<i>0.63</i>	<i>6</i>	<i>Gradient / Re-meshing</i>	<i>4.97</i>	<i>10</i>
<i>Total</i>	<i>11.23</i>	<i>100</i>	<i>Total</i>	<i>48.38</i>	<i>100</i>



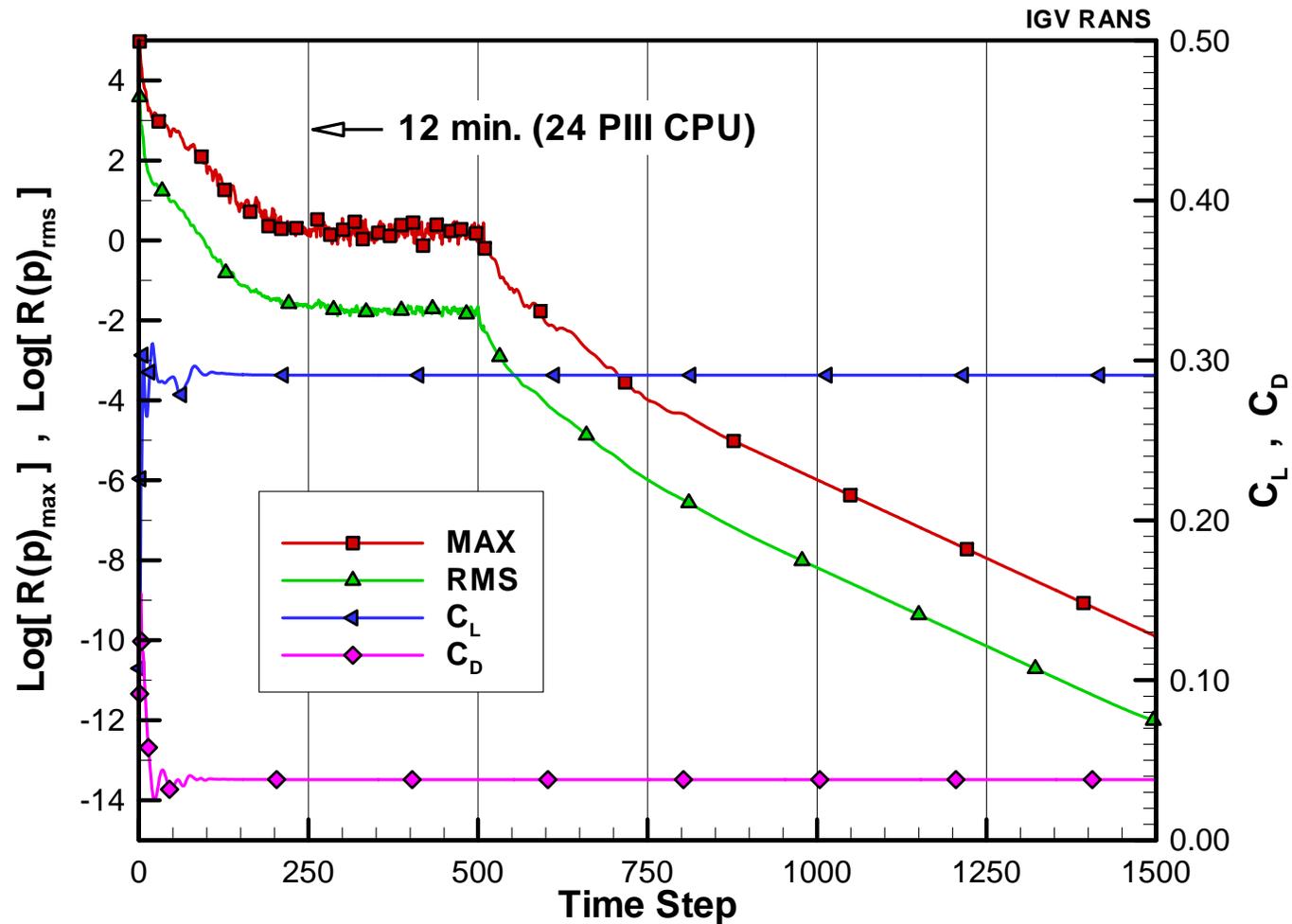
# RANS Results

- Inlet Guide Vane (IGV) & Rotor

- Governing equations:  
*3D incompressible RANS*
- Initial blade:  
Perturbed HIREP sections
- Geometric constraint:  
Fixed chord line
- Target pressure distributions:  
Separate simulations of  
HIREP IGV ( $Re_c = 1.8 \times 10^6$ )  
& Rotor ( $Re_c = 4.7 \times 10^6$ )

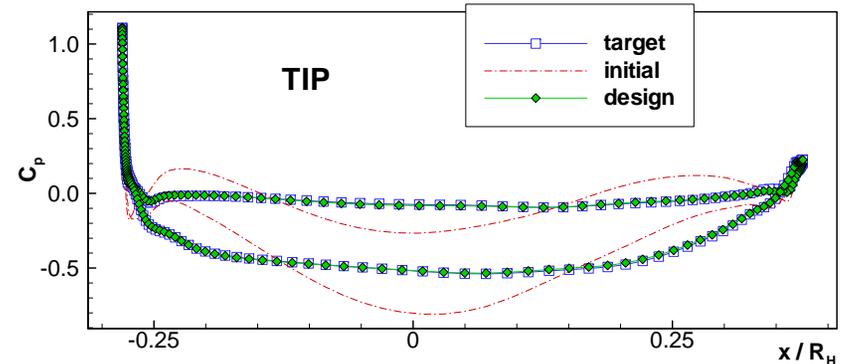
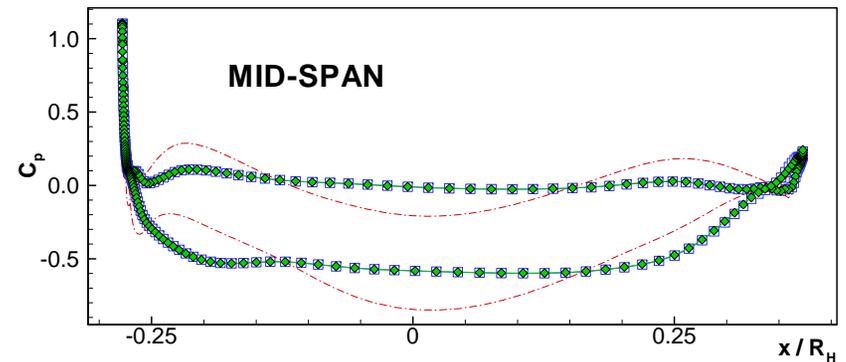
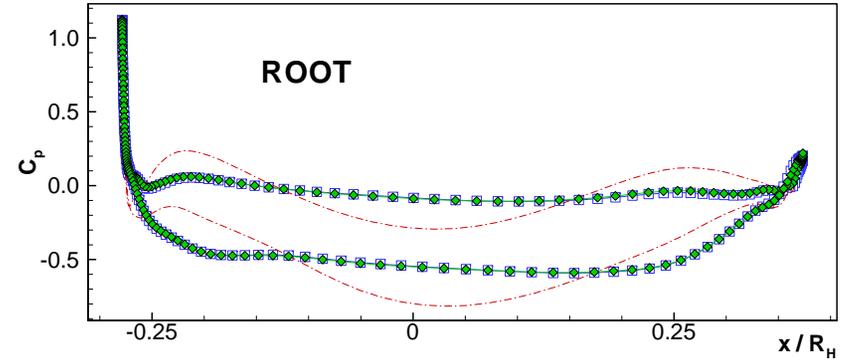
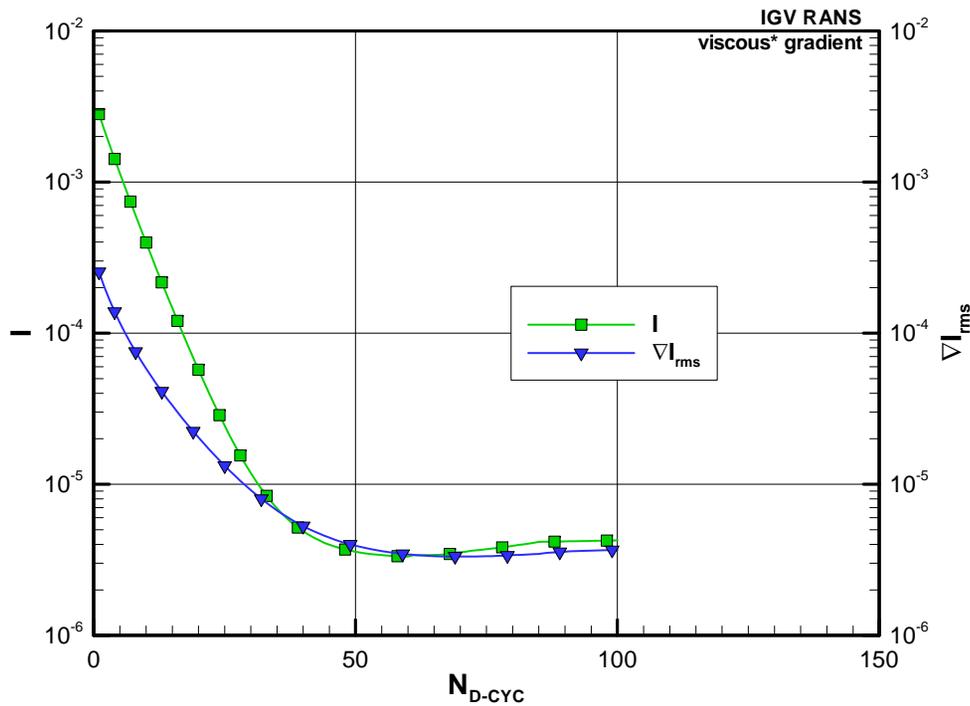


# RANS Results – IGV Convergence

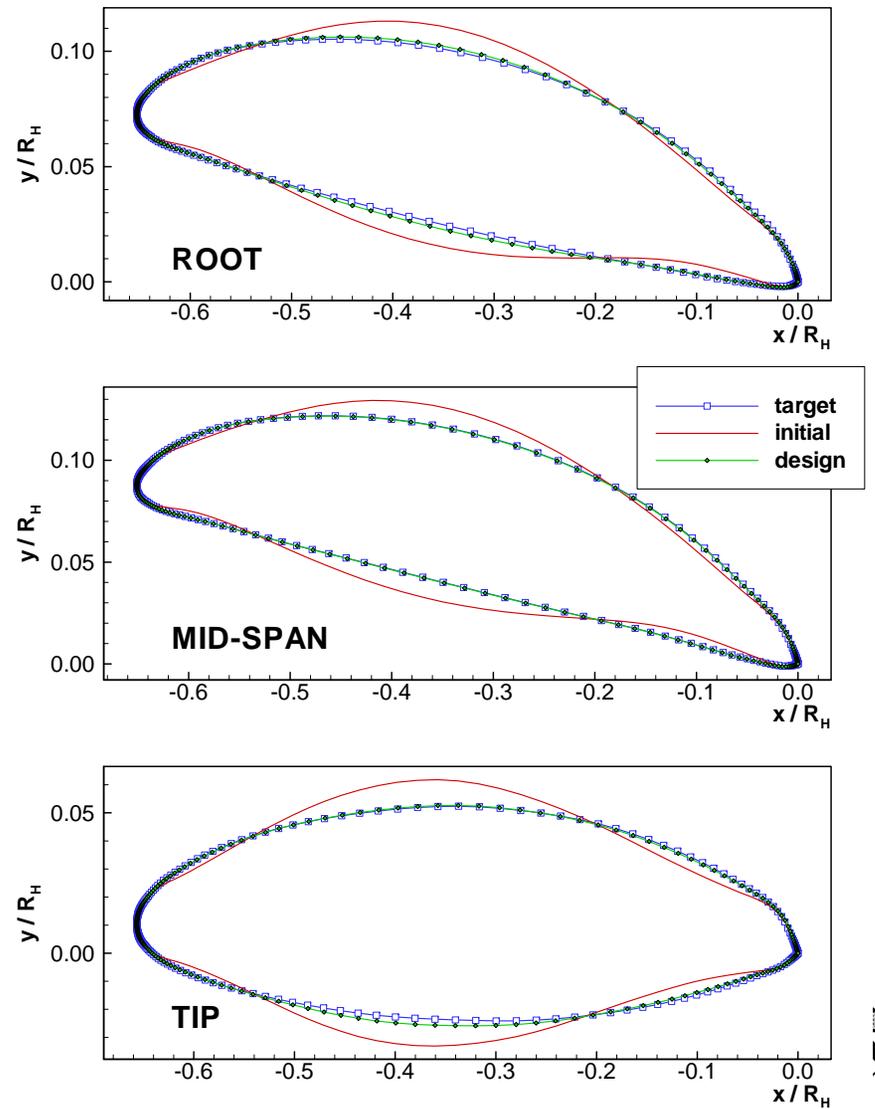
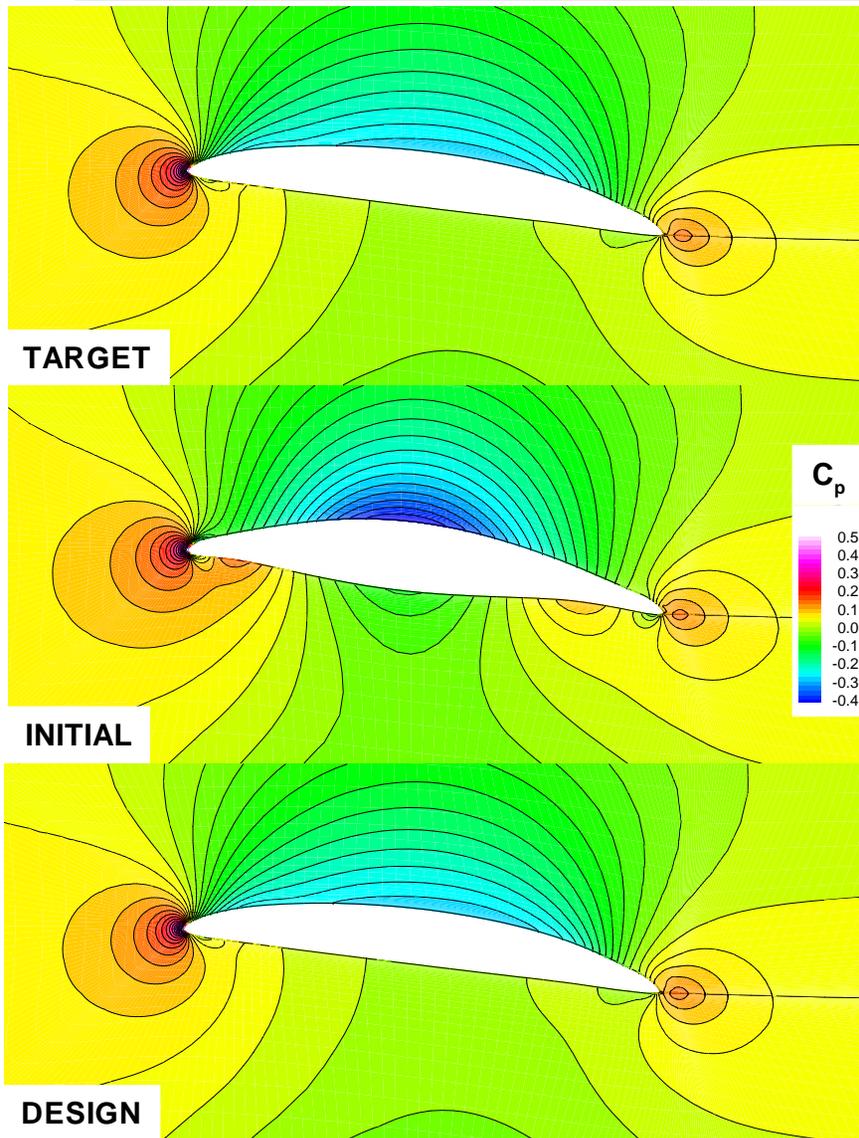


# RANS Results - IGV

- IGV Inverse Design  
(no rotation)  
 $N_D = 11025$

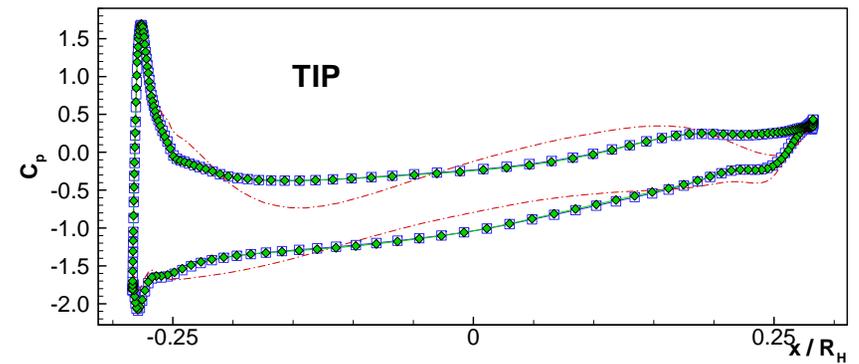
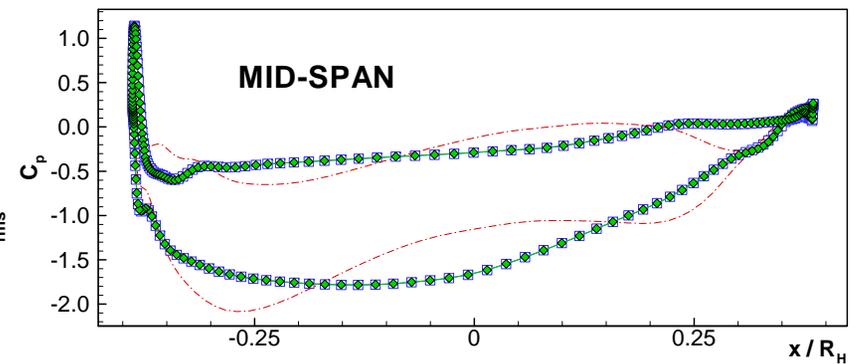
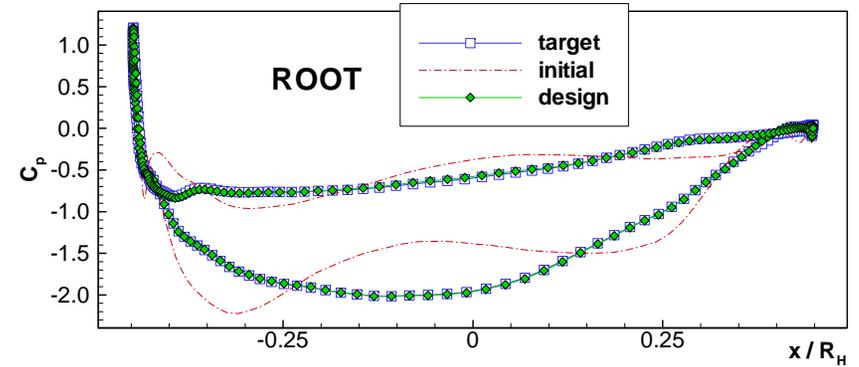
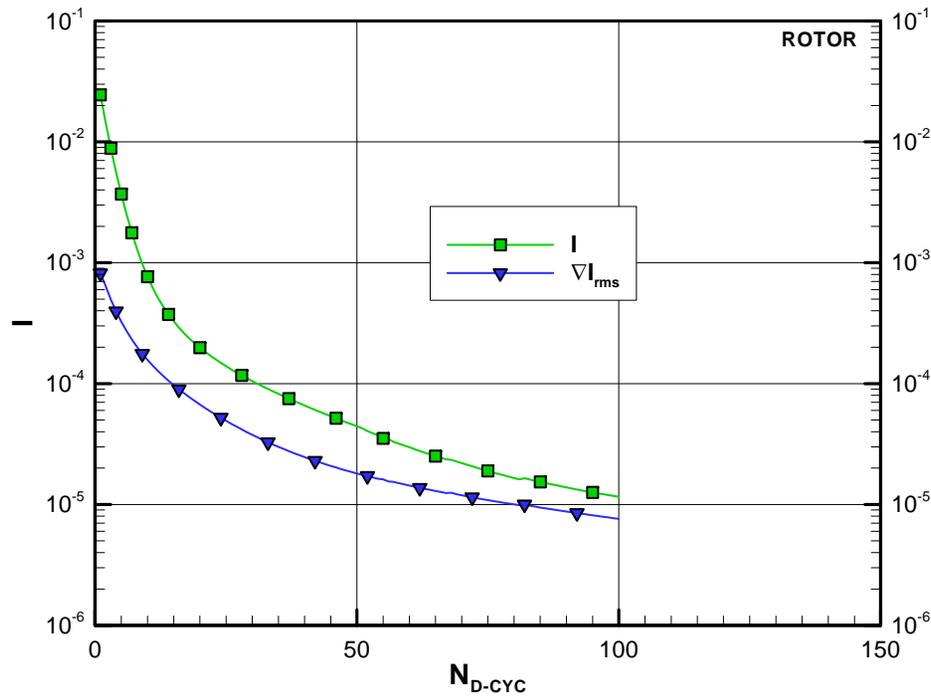


# RANS Results - IGV



# RANS Results - Rotor

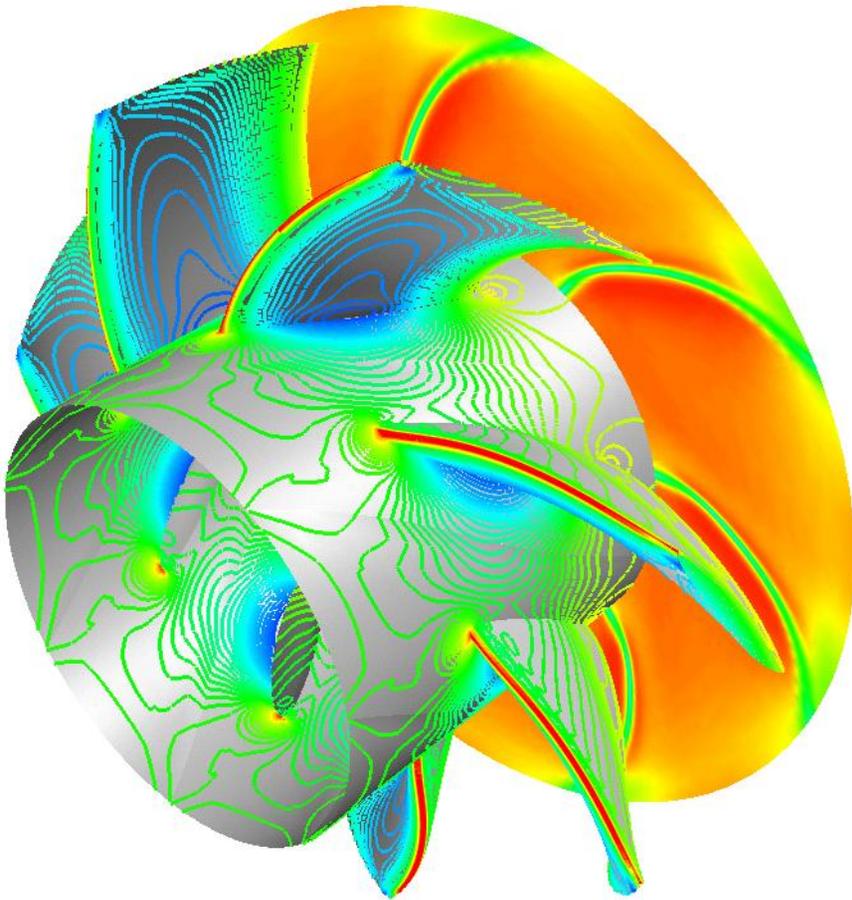
- Rotor Inverse Design  
(260 RPM)  
 $N_D = 11025$



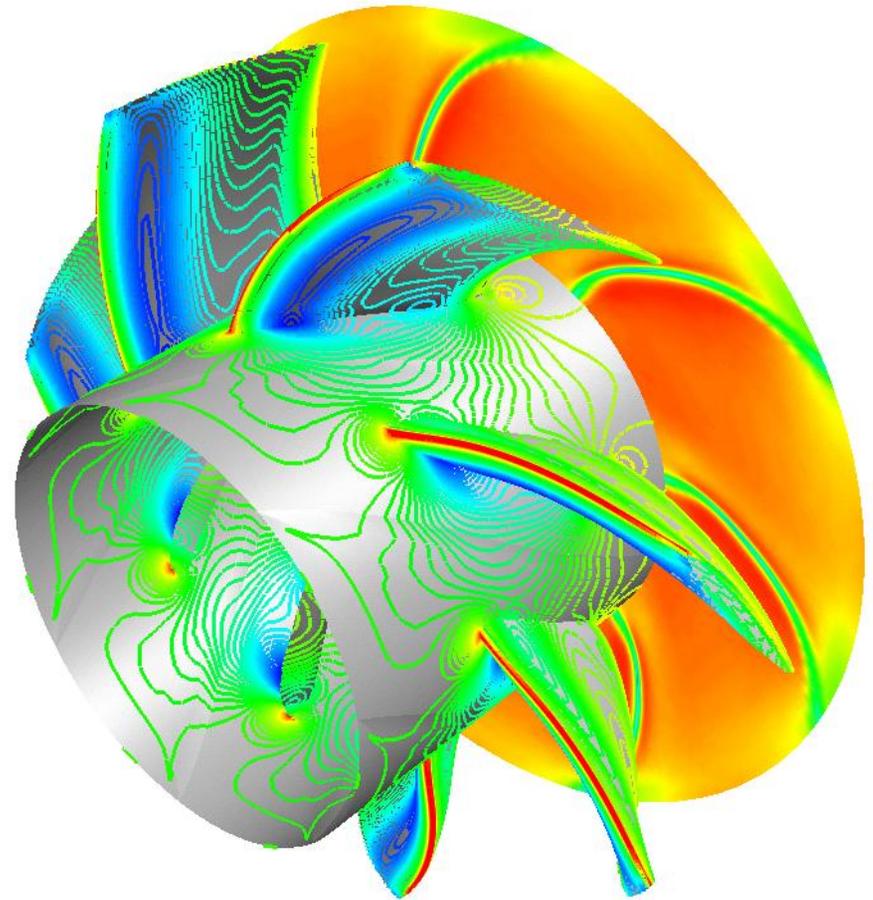
# RANS Results - Rotor

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TARGET



INITIAL

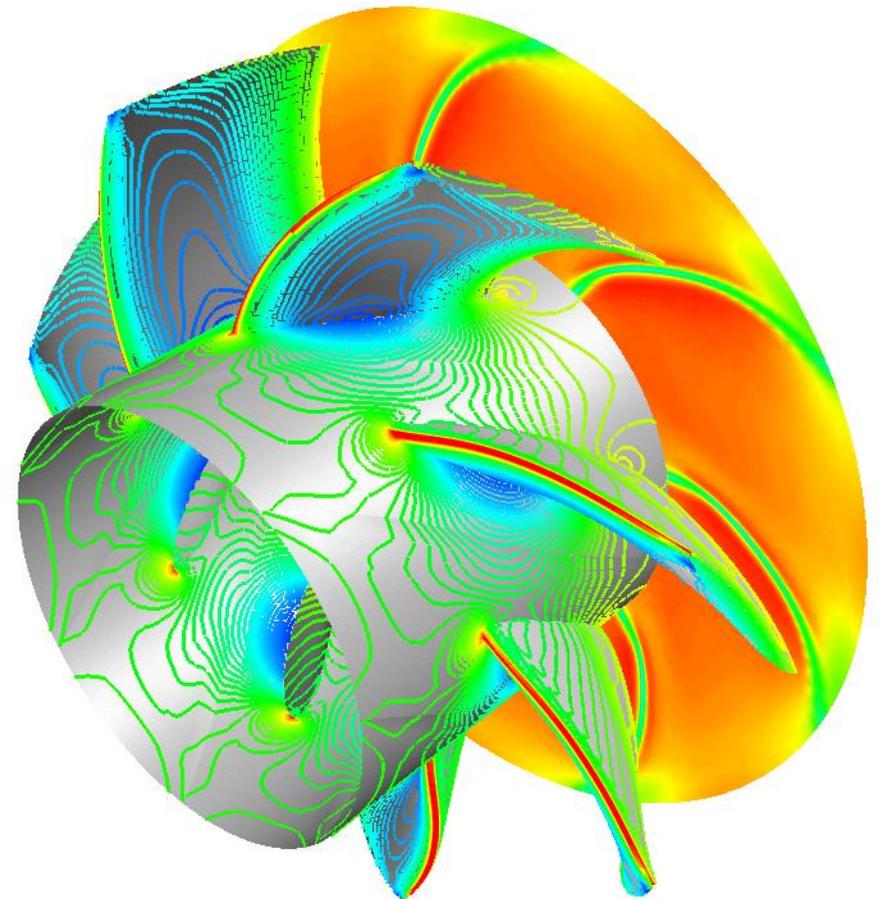
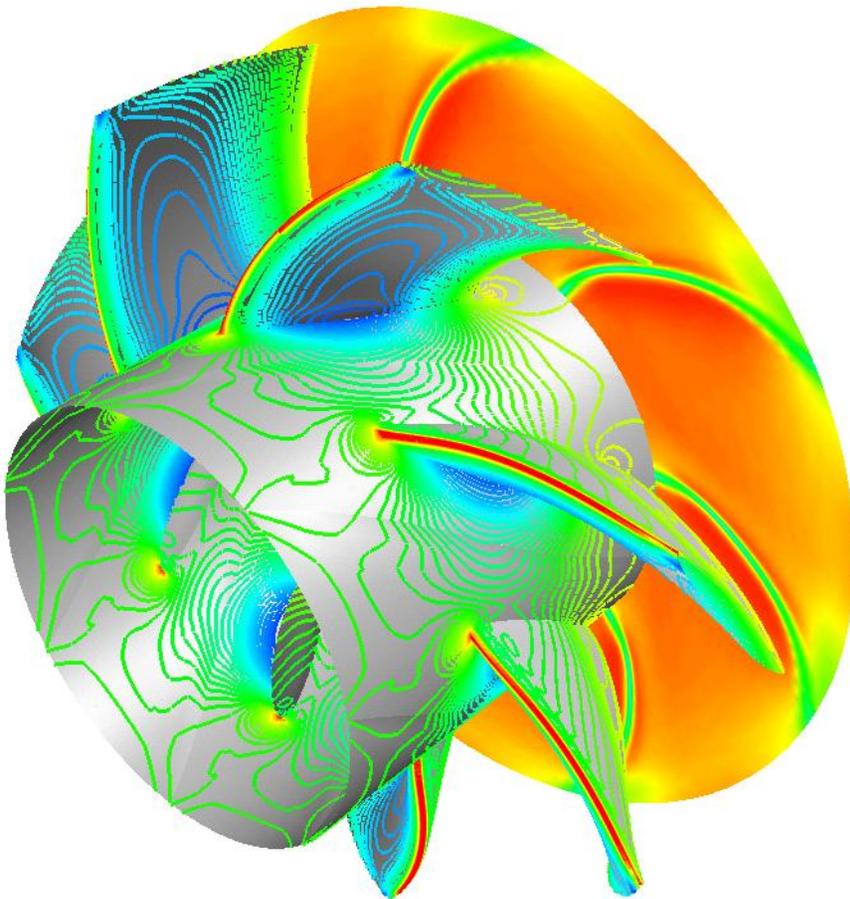


# RANS Results - Rotor

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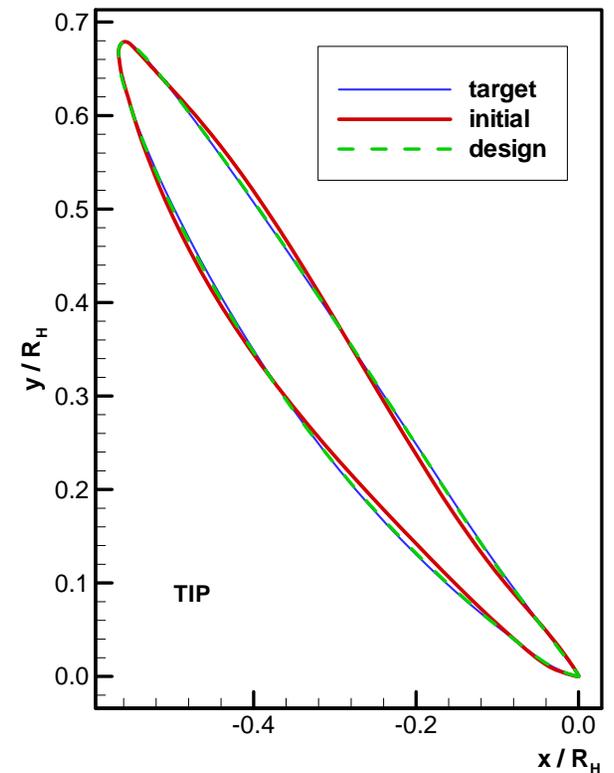
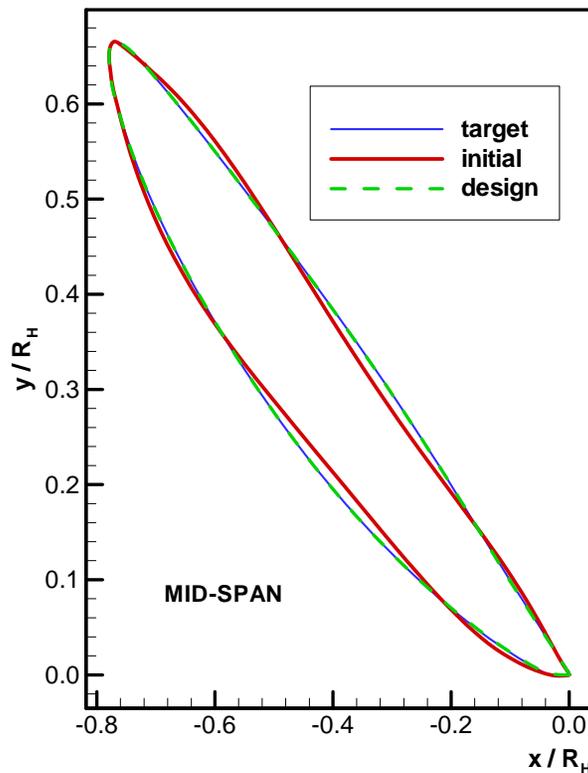
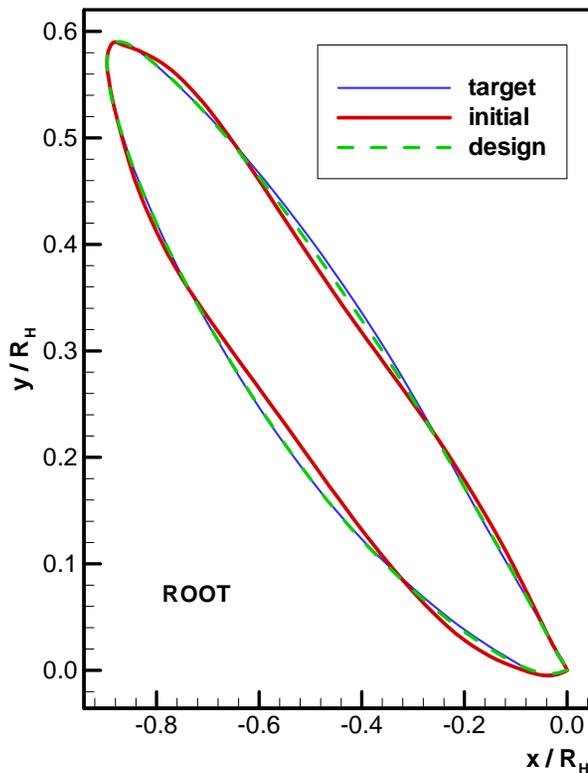
TARGET

DESIGN



# RANS Results - Rotor

- Rotor Blade Section Shape Comparison: ROOT, MID-SPAN, & TIP



# RANS Results - Summary

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- Design Cycle Timing

<i>Sublayer-Resolved MESH 770,721 mesh points 11,025 design variables</i>	<i>Wall Clock 24 CPUs (PIII) seconds</i>	<i>% of Total</i>
<i>Flow Solution</i>	<i>123.73</i>	<i>48</i>
<i>Adjoint Solution</i>	<i>116.20</i>	<i>46</i>
<i>Gradient / Re-meshing</i>	<i>14.55</i>	<i>6</i>
<i>Total</i>	<i>254.48 (4m 15.5s)</i>	<i>100</i>



# Conclusion

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- **Established the viability of the continuous adjoint approach for the shape optimization of propulsors**
  - **Demonstrated the minimization the inverse design cost function for an incompressible axial flow pump**
  - **Demonstrated using high-fidelity flow modeling:**
    - ***3D Euler, 312K mesh***
    - ***3D RANS, 770K mesh***
  - **Demonstrated using large design space**
    - **$N_D = 6,321 - 11,025$**
  - **Demonstrated the cost effectiveness:**
    - ***3D RANS, 11K d.v.  $\Rightarrow$  <4.5 min./cycle on 24 PIII CPUs***

